# Isospin-dependent nucleon-nucleon cross section and symmetry energy: sensitivity towards collective transverse flow

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## Introduction

The ultimate goal of studying isospin physics via heavy-ion reactions with neutron-rich, stable or radioactive nuclei is to explore the isospin dependence of in-medium nuclear effective interactions and the equation of state of neutron-rich nuclear matter, particular the isospin dependent term in the equation of state. Because of its great importance to nuclear physics community as well as to astrophysicists, significant progress has been achieved by the establishment of existing and upcoming radioactive ion beam facilities around the world [1]. The collective transverse in-plane flow has been used extensively over the past three decades to study the properties of hot and dense nuclear matter, i.e. nuclear matter EOS and in-medium nucleon nucleon (nn) cross section. The study of isospin effects helps us to obtain the information about the isospin-dependent mean field. The study of isospin effects in collective flow shows that the isospin effects occur due to the competition between nn collisions, symmetry energy, Coulomb potential [2, 3]. In the present work, we aim to see the relative contribution of symmetry energy and isospin-dependent nn cross section towards the collective transverse in-plane flow. The study is carried out within the framework of isospin-dependent quantum molecular dynamics (IQMD) model [4].

## The model

The IQMD model treats different charge states of nucleons, deltas, and pions explicitly, as inherited from the Vlasov-Uehling-Uhlenbeck (VUU) model. The isospin degree of freedom enters into the calculations via symmetry potential, cross sections, and Coulomb interaction. The nucleons of the target and projectile interact by two- and three-body Skyrme forces, Yukawa potential and Coulomb interactions. A symmetry potential between protons and neutrons corresponding to the Bethe-Weizsacker mass formula has also

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been included. The hadrons propagate using Hamilton equations of motion:

$$\frac{d\vec{r}_i}{dt} = \frac{d\langle H\rangle}{d\vec{p}_i}; \qquad \frac{d\vec{p}_i}{dt} = -\frac{d\langle H\rangle}{d\vec{r}_i} \tag{1}$$

with

$$\begin{aligned} \langle H\rangle &= \langle T\rangle + \langle V\rangle \\ &= \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r},\vec{p},t) \\ & \quad V^{ij}(\vec{r}\,',\vec{r}) f_j(\vec{r}\,',\vec{p}\,',t) d\vec{r}\, d\vec{r}\,' d\vec{p}\, d\vec{p}\,' \end{aligned} \tag{2}$$

The baryon potential $V^{ij}$, in the above relation, reads as

$$\begin{aligned} V^{ij}(\vec{r}\,' - \vec{r}) &= V^{ij}_{Sky} + V^{ij}_{Yuk} + V^{ij}_{Coul} + V^{ij}_{sym} \\ &= [t_1\delta(\vec{r}\,' - \vec{r}) + t_2\delta(\vec{r}\,' - \vec{r})\rho^{\gamma-1} \\ & \quad (\frac{\vec{r}\,' + \vec{r}}{2})] + t_3 \frac{\exp(|(\vec{r}\,' - \vec{r})|/\mu)}{(|(\vec{r}\,' - \vec{r})|/\mu)} \\ & \quad + \frac{Z_i Z_j e^2}{|(\vec{r}\,' - \vec{r})|} \\ & \quad + t_4 \frac{1}{\varrho_0} T_{3i} T_{3j} \delta(\vec{r}_i\,' - \vec{r}_j). \end{aligned} \tag{3}$$

Here $Z_i$ and $Z_j$ denote the charges of *ith* and *jth* baryon, and $T_{3i}$ and $T_{3j}$ are their respective $T_3$ components (i.e., 1/2 for protons and $-1/2$ for neutrons).

# Results and discussion

We simulate the reactions of Ca+Ca and Xe+Xe series having N/Z = 1.0, 1.6 and 2.0. In particular, we simulate the reactions of $^{40}$Ca+$^{40}$Ca, $^{52}$Ca+$^{52}$Ca, $^{60}$Ca+$^{60}$Ca and $^{110}$Xe+$^{110}$Xe, $^{140}$Xe+$^{140}$Xe and $^{162}$Xe+$^{162}$Xe at impact parameter of $b/b_{max}$=0.2-0.4. The incident energy is taken to be 100 MeV/nucleon.

In fig. 1, we display the time evolution of $< p_x^{\rm dir} >$ for the reactions of $^{40}$Ca+$^{40}$Ca, $^{52}$Ca+$^{52}$Ca and $^{60}$Ca+$^{60}$Ca. We see that at the start of the reaction, $< p_x^{\rm dir} >$ (squares, solid lines) is negative (due to the dominance of mean-field), reaches a minimum and then increases and saturates at around 80 fm/c. The values of $< p_x^{\rm dir} >$ is maximum for higher N/Z reaction, i.e., $^{60}$Ca+$^{60}$Ca. Since we are having isotopes of Ca, so Coulomb potential will be same for all the three N/Z reactions. So the isospin effects in the collective flow will

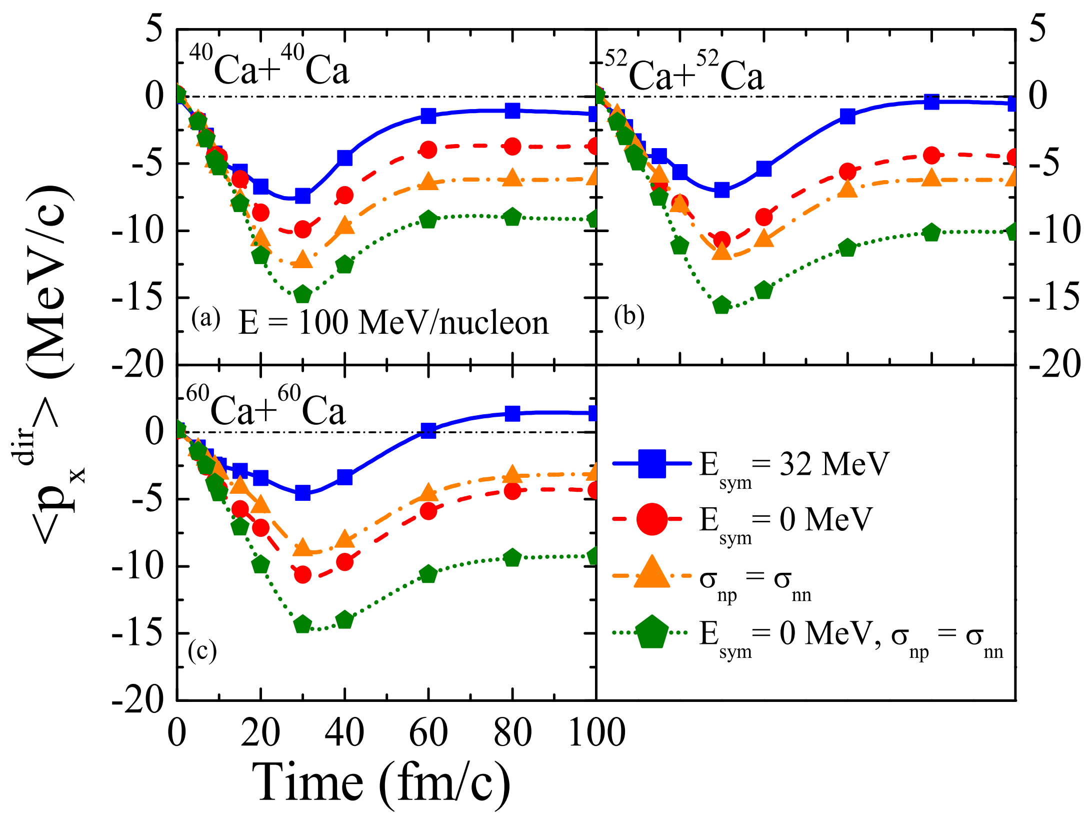


Figure 1: The time evolution of $< p_x^{\rm dir} >$ for the reactions of Ca+Ca having N/Z = 1.0, 1.6 and 2.0 at 100 MeV/nucleon. Lines are explained in the text.

be due to the interplay of symmetry energy and isospin-dependent nn cross section. To see the effect of symmetry energy on the collective transverse in-plane flow, we make the strength of symmetry energy zero. The results are displayed by circles (dashed lines). We see that when we make the strength of symmetry energy zero, the collective transverse in-plane flow decreases in all the three reactions. The decrease in flow is due to the fact that symmetry energy is repulsive in nature and hence leads to positive in-plane flow and so when we make it's strength zero, the flow decreases. To see the effect of isospin dependence of nn cross section, we make the cross section isospin independent, i.e., $\sigma_{np} = \sigma_{nn}$ and calculate the flow. The results are displayed by triangles (dash-dotted lines). We find that the flow decreases when we make the cross section isospin independent. This is because in isospin dependent case, the neutron-proton cross section is three times that of neutron-neutron or proton-proton cross section. When we make the cross section

isospin independent the effective magnitude of nn cross section decreases which leads to less transverse flow. Finally to see the combined effect of symmetry energy and isospin dependence of cross section, we make both the strength of symmetry energy zero and cross section to be isospin independent, simultaneously. The results are displayed by pentagons (short-dotted lines). We find that the maximum decrease in flow is for $^{60}$Ca+$^{60}$Ca which goes on decreasing as we are moving to symmetric systems.

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